3RD KA-BAND UTILIZATION CONF.
SEPT. 15-18, 1997
SORRENTO, ITALY

DISTRIBUTED HDV POST-PRODUCTION OVER TRANS-PACIFIC ATM SATELLITES

Eddie Hsu, Charles Wang, Larry Bergman
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California, 91109-8099 USA
Ph: +1 818 354-3212 Fax: +1 818 393-3302
E-mail: {eddie.hsu, charles.wang, larry.bergman}@jpl.nasa.gov

Naoto Kadowaki, Takashi Takahashi
Communications Research Laboratory
Ministry of Posts and Telecommunications
4-2-1 Nukui-Kita
Koganei, Tokyo 184 Japan
Ph: +81 423 27 7513 Fax: +81 423 24 8966
E-Mail: {naoto, kato}@crl.go.jp

Burt Edelson, Neil Helm
George Washington University
EECS-IASR
2033 K Street, NW
Washington, DC 20052 USA
Ph: +1 202 994-5509 Fax: +1 202 994-5505
E-mail: {edelson, helm}@seas.gwu.edu

James Pearman
Sony-Pictures High Definition Center
10202 West Washington Blvd
Culver City, California 90232-3195 USA
Ph: +1 310 280-7433 Fax: +1 310 280-3014
E-mail: jpearman@earthlink.net

Frank Gargione
Lockheed Martin Missiles and Space
P.O. Box 800
Princeton, New Jersey 08543-0800
Ph: +1 609 490-2337 Fax: +1 609 490-2444
E-mail: frank.gargione@lmco.com

ABSTRACT
This paper describes a joint collaboration between government and industry teams in the United States and Japan to demonstrate distributed high definition video (HDV) post-production on a global scale using a combination of high data rate satellites and terrestrial fiber optic asynchronous transfer mode (ATM) networks. The experiment is one of the activities arising from the Japan-U.S Cooperation in Space Project, and links the U.S. mainland to Hawaii using the NASA Advanced Communications Technology Satellite (ACTS) and Hawaii to Japan using Intelsat.

A series of links was established, and on March 27, 1997, HDV source material was transmitted between Sony Pictures High Definition Center (SPHDC) in Los Angeles and Sony Visual Communication Center (VCC) in Shinagawa, Tokyo, demonstrating that satellites can deliver digital image traffic at OC-3 data rates and quality comparable to that of fiber optic cables. Post-production compositing performed in Tokyo on a green-screen HDV clip transmitted from Los Angeles and comparison of an HDV clip to its original source after one trans-Pacific satellite round-trip demonstrated the success of this high data rate communications channel for rapid transfer of HDV between remote shooting locations and post-production facilities. Correlation of atmospheric effects with cell loss, codec drop-out, and picture quality were made.

The 1.2 Gbps high definition video stream was compressed using a proprietary Mitsubishi MPEG-2 codec that is ATM compatible. The peak data rate of the codec was 22 Mbps.

This same experiment will later provide quality high rate communication channels for the rapid transfer of HDV masters from remote shooting locations around the world to post production facilities for editing, dubbing, distribution, etc.

1. INTRODUCTION

Government and industry teams in Japan and the United States have begun a series of trans-Pacific experiments to develop and demonstrate the role of satellites in the Global Information Infrastructure (GII). These experiments will explore and develop satellite transmission techniques, standards, and protocols in order to determine how best to incorporate satellite links with fiber optic cables to form high performance global telecommunications networks.

The purpose of this experiment was to demonstrate broadband satellites' capabilities in delivering digital image traffic at rates up to OC-3 (155 Mbps), which is normally transmitted by terrestrial fiber optic networks, and to help close the performance gap between these two important technologies. Of particular interest are HDV domains where fiber optic networks are a complement to satellite-based broadband links.[1] The combination of terrestrial fiber optic networks and satellite-based links affords high bandwidth and high mobility access in areas where it is unfeasible to deploy a fiber optic infrastructure. This experiment is the first of the GIBN experiments to establish a dual-hop broadband satellite link for the transmission of HDV over ATM. It demonstrated the flexibility of an infrastructure using modern broadband satellites.

This experiment tested the ability of satellites to carry very high definition video signals for post-production processing between Sony studios in Tokyo and Los Angeles. Japan was linked to Hawaii via an Intelsat satellite, and Hawaii to California via NASA's Advanced Communications Technology Satellite. Video source in the Society of Motion Picture and Television Engineers (SMPTE) 240M-1994 format was used with proprietary Mitsubishi Electric MPEG-2 (Moving Pictures Experts Group) codecs. With digital post-production processing, the director can optimize a scene in less time and for less cost. Additionally, since all the scenes have been recorded in a digital format, it is extremely easy to transmit the image clips to and from remote sites

The technology demonstrated in this experiment enables a director shooting on-location (or directing the actions of a remote cinematography team from a studio) to work closely with a post-production editor in real-time. This experiment also planned to demonstrate the feasibility of high data rate communication channels for the rapid transfer of HDV masters from remote shooting locations around the world to post production facilities for activities such as editing, dubbing, distribution, etc.

Additional trans-Pacific experiments are planned to carry high speed computer data, high resolution images, and video signals for many other applications, including astronomy, tele-medicine, tele-education, digital libraries, and electronic commerce.

2. JAPAN-U.S. COOPERATION IN SPACE

The Trans-Pacific High Data Rate (HDR) Satellite Communications Experiments is a set of tests, demonstrations and experiments initiated as part of the Japan-U.S. Science, Technology and Space Application Project that began in 1991. JUSTSAP is a cooperative program, organized on a non-governmental level, but with government, industry, and university participation. In 1994, the JUSTSAP Satellite Communications Working Group committee, chaired by Dr. Burt Edelson of George Washington University and Dr. Takashi Iida of the Ministry of Posts and Telecommunications of Japan, proposed a series of broadband network experiments using a combination of satellite and terrestrial ATM infrastructures. The proposal was accepted by government, industry, and academic teams in both countries and resulted in the Trans-Pacific High Data Rate Satellite Communications Experiments. These experiments are now incorporated into the G7 Global Interoperability for Broadband Networks (GIBN) project.

The series of experiments planned include experiments in the areas of high definition video post-production, remote astronomy, tele-medicine, tele-education, electronic commerce, and digital libraries. Participants in these experiments will include the G7 countries, and other non-G7 countries will be invited as well. These experiments will carry high speed computer data, high resolution images, and video signals for many applications. The HDV experiment is the first of the GIBN experiments to establish a broadband link utilizing satellites, and it marks the exciting beginning of the series of GIBN experiments that are to follow.

3. THE PARTICIPANTS IN THE HDV EXPERIMENT

Japanese participants include the Communications Research Laboratory (CRL), Ministry of Posts and Telecommunications (MPT), Kokusai Denshin Denwa Company, Limited (KDD), Mitsubishi Electric Corp., Nippon Telephone and Telegraph (NTT), and Sony Corporation; the U.S participants include Comsat, George Washington University, GTE Hawaiian Tel, Lockheed Martin, NASA HQ, Goddard Space Flight Center (GSFC), Lewis Research Center (LeRC), Jet Propulsion Laboratory (JPL), Newbridge Networks Inc., Pacific Bell–California Research and Education Network (CalREN), Pacific Space Center (Pac Space), Sony Picture High Definition Center (SPHDC), and Tripler Army Medical Center (TAMC). An international organization, Intelsat, also participates.

[1] L. Bergman, F. Gargione, James Pearman, *U.S.-Japan Trans-Pacific High Data Rate Intersatellite Link*, American Institute of Aeronautics and Astronautics, 1995.

4. NETWORK CONFIGURATION

The trans-Pacific ATM connection can be described as having two segments separated by the terrestrial connection in Hawaii. The Eastern Pacific segment consists of various links from Hawaii to Culver City, California, using the NASA ACTS. The Western Pacific segment consists of various links from Hawaii to Shinagawa, Tokyo, using the Intelsat 701 at 174°E. Figure 1 shows the trans-Pacific ATM link configuration over both the Intelsat and ACTS.

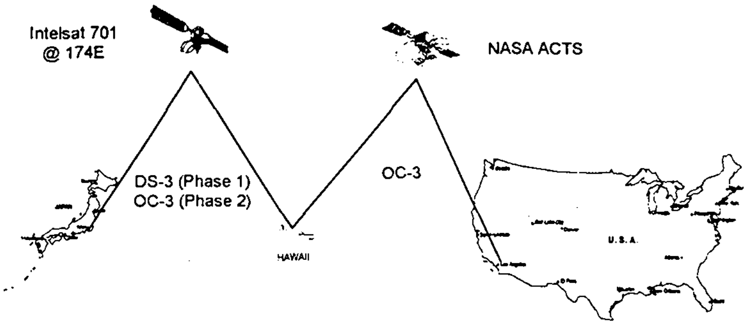


Figure 1. Trans-Pacific ATM Link Configuration Diagram.

4.1 EASTERN PACIFIC

The Sony Pictures High Definition Center (SPHDC) in Culver City, California, is connected via the Pacific Bell's California Research and Education Network (CalREN) at OC-3 rate to the ACTS HDR terminal located at JPL, Pasadena, California. The CalREN link passes through two ATM switches in Gardena and Glendale, California.

The CalREN access point joins the JPL Institutional Network's ATM infrastructure at the JPL Information Processing Center (IPC). The link passes through two additional ATM switches before arriving at the JPL ACTS HDR terminal for the satellite-bound leg to the NASA ACTS at rates up to OC-3 towards Hawaii.

The HDR terminal is constructed by Bolt Beranek and Newman Inc. (BBN), and the major components consist of a 3.4 meter antenna made by Prodelin, digital terminal electronics made by BBN, and a 696 Mbps modem made by Motorola. The equipment can provide transmissions at rates from OC-3 to OC-12 (622 Mbps). The HDR terminal uses forward error correction with a (232, 216) Reed-Solomon code.

An alternate ACTS facility was also available for use by the experiment. The second OC-3 link from the ACTS satellite was established from the LeRC earth station in Cleveland, Ohio. This earth station was connected to JPL through the National Research and Education Network (NREN). JPL acted as the gateway between CalREN and NREN.

The NASA Advanced Communications Technology Satellite (ACTS) is a bent-pipe satellite that uses the Ka-band, with the uplink frequency of 29.4 GHz and the downlink frequency of 19.6 GHz. The frequencies are attenuated by rain and cloud cover. In this experiment, the spot beam antenna of the satellite was used to communicate with the JPL HDR. The steerable beam antenna was used for the Hawaii TAMC HDR. The ACTS satellite and the HDRs can support both OC-3 and OC-12 using BPSK (binary phase-shift keying) and QPSK (quadrature phase-shift keying) respectively, although only OC-3 could be supported for this experiment because of the lower gain of the steerable beam antenna used for the Hawaiian site.

Another ACTS high data rate terminal is located at the Tripler Army Medical Center (TAMC) on Oahu, Hawaii. It constitutes a terrestrial end-point in the Hawaiian terrestrial ATM network. The participants in Hawaii, Pac Space and GTE Hawaiian Tel, provide the ATM connection between the TAMC earth station and the Intelsat earth station at Kapolei. The terrestrial link — operating at OC-3 from TAMC to the Honolulu Central Office and DS-3 (45 Mbps) from the Honolulu Central Office to the Kapolei earth station — passes through two ATM switches, one at TAMC and the other at the GTE Hawaiian Tel Honolulu Central Office.

4.2 WESTERN PACIFIC

The Kapolei earth station is the other terrestrial network end-point on Oahu, connecting the Hawaiian terrestrial network to the Intelsat 701 satellite on the 174°E orbit. The Intelsat satellite operates using Ku-band towards Japan and C-band towards Kapolei. Intelsat, an international organization, contributes the Intelsat satellite time for this experiment. A cross-strap transponder is used on the Intelsat. The downlink frequency to Japan is 11 GHz, and the uplink frequency is 14 GHz. The downlink frequency to Hawaii is 4 GHz, and the uplink frequency is 6 GHz. The NEC/KDD proprietary QPSK (quadrature phase-shift keying) modem is 7/8 Viterbi and (255, 239) Reed-Solomon coded with bit interleaving to reduce cell loss. The baud rate is 27.488 Mbaud.

The Kokusai Denshin Denwa (KDD) earth station serves as the end-point in Japan for the Intelsat 701. The connection from the Intelsat to the KDD earth station at Shinjuku, Tokyo, uses Ku-band, operating at DS-3 for Phase 1 of the experiment. A new Ku-band terminal is located at the Communications Research Laboratory (CRL) Kashima Space Research Center for the Phase 2 (OC-3) part of the experiment. The terminal will have an OC-3 ATM switch and a STM-4 (622 Mbps) protocol converter.

The KDD earth station at Shinjuku, Tokyo, is connected to KDD's Otemachi ATM Network Office at DS-3 (Phase 1). The KDD ATM Network and the new CRL network at Kashima are both connected to NTT's fiber optic network. The NTT network joins the Sony High Definition Visual Communication Center (VCC) at Shinagawa, Tokyo using rates up to STM-1.

5. HIGH DEFINITION VIDEO (HDV) AND BLUE/GREEN-SCREEN COMPOSITING

High definition video is a motion picture medium that captures high resolution images in a digital format. It is a production system that matches or exceeds the quality of film while delivering the convenience of electronic production and the benefits of digital processing. The source material and equipment used in the experiment conform to the SMPTE 240M-1994 standard (Table 1).

SMPTE Standard	240M-1994
Field frequency	60 Hz
Active lines per frame	1035 v
Active samples per line	1920 h
Aspect ratio	16:9
Scanning format	2:1 interlaced
Raw real-time bit rate	1.2 Gbps

Table 1. High Definition Video Format.

Blue/green-screen compositing[2] is a process of recording subject images in front of an entirely blue or green background (also known as *blueback* or *greenback*). The background may later be *composited* in post-production processing with selected images to create the appearance of the subjects being filmed in various locations or amidst special effects. In the traditional way of film-making, performing blue/green-screen cinematography with photographic materials often takes weeks and many iterations between the director and the film laboratory to produce the images matching the director's vision. Green-screen cinematography is done in a studio by setting up the proper background. Green-screen compositing allows the green background to be replaced by selected images during the post-production process. HDV compositing allows the post-production processing to be done in real-time. The images may be viewed at remote locations using a portable HD monitor. This makes possible the instant review of green-screen compositing results and permits the modification of remote HD shots to the director's liking. The real-time post-production activities therefore significantly cut down on the amount of time needed for compositing, as well as shorten the length of time a cinematography team needs to stay at a remote location.

A part of the HDV post-production demonstration held on March 27, 1997, involved green-screen cinematography performed at the SPHDC, the transmission of the images to Sony VCC in Japan for post-production processing, and the review of the results at both locations.

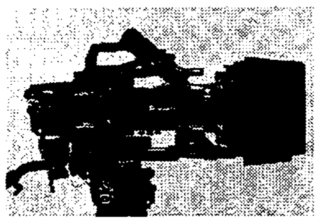
---

[2] Norio Shindo. *HDTV Post Production System.* Japan-U.S. Cooperation in Space Workshop. Nov. 1994.

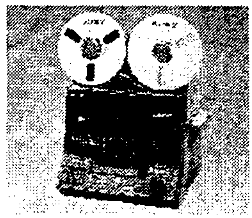
6. HDV EQUIPMENT

The high definition equipment used at the SPHDC includes a charge-coupled device (CCD) camera and tape recorders. Sony HDD-1000 recorders (VTR's) are used to play and record HD video, a Sony HDC-500 1" CCD camera is used to capture green-background shots for post-production processing (Figure 2), and High Definition Video System Monitors and Projector are used to display the images.

The HDV codec supplied by Mitsubishi Electric Corporation is a proprietary piece of equipment implementing an MPEG-2 algorithm for the SMPTE 240M (and 260M) format. Analog video signal input is used, with the field frequency of 60 or 59.94 Hz. Digital audio input is used, with four audio channels in MPEG audio mode. The peak data rate generated by the codec is 22 Mbps. Two other peak data rates may be selected (at 60 and 120 Mbps). The compressed video data is transmitted and received using ATM cells. The experimental codec has small pools of buffer at both end points; therefore, strict timing synchronization needs to be maintained to prevent the overrun/underrun situation. An off-sync condition affects the resulting video image in the form of static picture (*freeze-frame*). The variable-bit-rate codec is interfaced to the ATM network through the use of ATM Adaptation Layer 5 (AAL-5).



Sony HDC-500 Camera



Sony HDD-1000 Digital Recorder

Figure 2. High Definition Camera and Recorder.

7. POST-PRODUCTION ACTIVITY DEMONSTRATION

On March 27, 1997, the Trans-Pacific HDV team held public demonstrations in the US and Japan. The data used for this experiment consisted mainly of HDV source material transmitted between the SPHDC in Los Angeles and Sony VCC in Shinagawa, Tokyo. HDV clips were transmitted in real-time in simplex, duplex, and loop-back modes via ATM networks at OC-3 and DS-3 rates. The video coded ATM cells traveled from SPHDC to JPL through Pacific Bell's CalREN network. The signal was then transmitted to Hawaii through the NASA ACTS and four earth stations. GTE Hawaiian Tel provided the terrestrial fiber link between the Tripler ACTS earth station and the Kapolei Intelsat earth station. The signal was sent to Japan via an Intelsat and relayed to Sony VCC via the KDD and NTT fiber optic networks. The 1.2 Gbps HDV was compressed using a proprietary Mitsubishi MPEG-2 codec that is ATM compatible. The peak data rate of the codec was 22 Mbps.

An HDV short film entitled "Good Night Tokyo" was first transmitted from Sony VCC in Tokyo. Next, to demonstrate the post-production capability of the trans-Pacific network, a green-screen HDV clip showing a subject was transmitted to Sony VCC from SPHDC. Background material was superimposed in real-time by editor engineers at Sony VCC, and the composite picture was then transmitted back to SPHDC and shown to the audience. Lastly, an uncompressed promotional HDV clip designed to showcase the quality and capability of HDV was played back locally by SPHDC at 1.2 Gbps, and then compared against the same compressed video looped back from Japan. The quality of the compressed HDV signal after one trans-Pacific satellite round-trip was very comparable to the original uncompressed studio source. In fact, in most cases, the imperfections of the original source material were often exposed. ATM network analyzers were placed at edges of the network to assist in correlating atmospheric effects with cell loss, codec dropout, and picture quality.

8. ACTS ATM/HDV PERFORMANCE

The ACTS HDR earth stations keep a log of the link status. The log files are updated every 10 minutes and include estimates of error rates before and after the Reed-Solomon decoder. The error rates are recorded in terms of the number of erroneous satellite cells in ten-minute intervals as detected by the Reed-Solomon decoder. A satellite cell (S-cell) contains 215 bytes of data and is about 1.03 ms. It was observed that the JPL-to-TAMC link usually ran error-free. The TAMC-to-JPL link, on the other hand, was less robust.

Figure 3 shows the distribution of S-cell errors during the total of fifty-one hours of ACTS satellite time when the TAMC-ACTS-JPL link was available. The S-cell error rate showed the number of uncorrectable errors after the Reed-Solomon decoder. It shows that about 70% of the time the ACTS links were error free. The S-cell error rate was approximately the same from 10^{-6} to 1.0.

The difference in link performances can be partially explained by the fact that the earth station antenna of the TAMC HDR has a very low elevation angle. Signals to Hawaii had to go through relatively thicker cloud layers or precipitation in this low elevation path. The ACTS satellite also communicates with Hawaii using the lower gain steerable beam antenna. Since the uplink frequency of 30 GHz was more susceptible to rain and water vapor attenuation, the direction from TAMC-to-JPL was usually much worse than the direction from JPL-to-TAMC. The experiment was, however, conducted in February and March, which are two of the wetter months in Honolulu, Hawaii (Figure 4). The ACTS link to Hawaii should perform significantly better in the drier months.

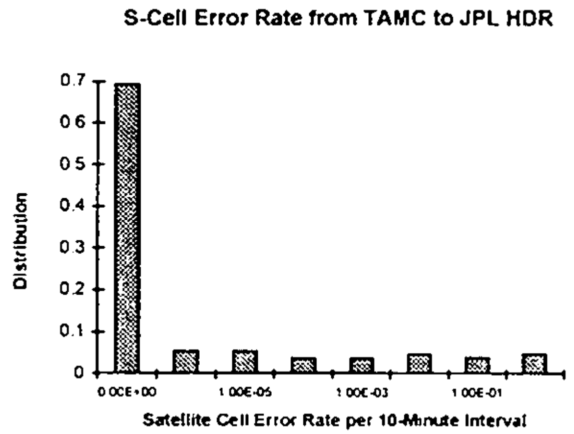


Figure 3. Histogram of ACTS S-Cell error rate from the Tripler HDR to the JPL HDR.

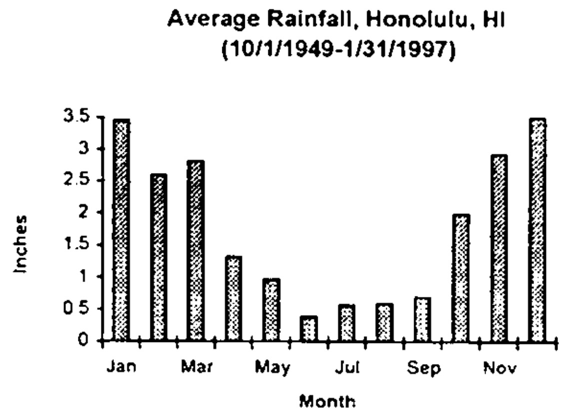


Figure 4. Average rainfall in Honolulu, Hawaii.

As described earlier, the performance of the ACTS links using Ka-band was dependent on the weather. Also, while the JPL-to-TAMC link generally ran error-free regardless of the weather condition in Los Angeles or Hawaii, the performance of the TAMC-to-JPL link depended highly on the weather condition in Hawaii. If it was overcast or raining in Hawaii, the error rate would generally be high. There would also be occasional link outages.

It needs to be noted that the ACTS satellite was originally designed to provide communication within the forty-eight contiguous states, but not to communicate with Hawaii. The steerable beam antenna had to be used in the Hawaiian link, because the state is located outside the coverage of fixed-beam antennas. The satellite communications link margin was small with the steerable beam antenna, especially in Ka-band in which the signal underwent fading in rain.

8.1 ATM PERFORMANCE

ATM link performance was measured using ATM analyzers. Test cells were looped back from various points along the trans-Pacific network. The ATM performance of the trans-Pacific link was measured using two monitoring systems of Hewlett Packard 37717C ATM analyzers. A monitoring system was installed at each user site (Sony VCC and SPHDC) to measure the ATM transmission performance.

Weather data helps correlate the performance of satellite links and the effects on the high definition video. The U.S. National Weather Service (NWS) reports forecasts and hourly observations for various U.S. locations. Reports for Honolulu, Hawaii, and Los Angeles, California, were collected during this experiment. Coded forecast and weather observation sequences obtained from a commercial on-line service provide information as to the cloud coverage (area and height), relative humidity (in temperature/dew point difference), and any precipitation (type and intensity) at selected locations. Weather observation satellite photographs are also available.

Table 2 shows ATM link performance on the days when weather data was available and the corresponding loop-back points. It also shows the performance of the ACTS links reflected by the S-cell error logs. There were experiment runs during which no NWS weather data was collected. The data shown in Table 2 does present a general trend of ATM link performance as a function of the ACTS links performance and the weather conditions.

Typically, when it rained or when there was a thick cloud cover in Honolulu, the ACTS link was observed to have many error bursts. For example, at one time the ACTS link faded away for nearly three minutes in heavy precipitation in the Honolulu area. Asymmetric performance was observed in the ACTS links to/from Honolulu at times. The terrestrial fiber network did not contribute to the error statistics significantly. This result was consistent with the characteristics of the satellite designs and link frequencies.

Date (U.S.)	Honolulu Weather	ACTS BER Log	ATM Tester Results
Mar 10 *Rain/Overcast Layer*	05:56-08:56pm PST 3000 ft few, 3500 ft few, 13000 ft broken, 23000 ft overcast. Rain showers in vicinity, south east.	No error for four hours. Bursts of errors in the last ten minutes of the experiment.	Looped back at Tripler, Hawaii. No error in 9.5×10^8 cells (2 hr and 50 min). Cell loss ratio of 4.2×10^{-4} and error ratio of 1.9×10^{-5} for last 10 minutes.
Mar 18 *Broken Layer*	04:50-07:50pm PST 4000 ft scattered, 8500 ft broken - 4000 ft few.	No errors for two hours.	Looped back at Sony VCC. No error in 1.34×10^8 cells.
Mar 20[1] *Broken Layers*	06:50-09:20pm PST 5500 ft broken, 7000 ft broken, 14000 ft broken, 23000 ft broken.	A few errors in a ten-minute block in the first hour. Otherwise, error-free.	Looped back at GTE, Honolulu. No error in one hour. Looped back at Sony VCC. No error in 10 minutes.
Mar 27 *Broken Layer*	06:50-09:50pm PST 3500 ft broken.	No errors in six hours.	Looped back at Sony VCC. One cell error in six hours.[2]

1. Most of the time used for end-to-end HDV transmission.
2. ATM tester used to monitor the end-to-end video traffic.

Table 2. ACTS and ATM Performance.

8.2 HDV PERFORMANCE

The experimental codec was originally designed for use with highly reliable terrestrial fiber optic networks. It had performed relatively well in this experiment. Compared to the original uncompressed digital HDV source, the output of the video codec had no visible compression artifacts. In fact, in most instances the imperfections in the original source material were revealed. The only observable effect of the codec and the network was the occasional freeze-frame. A freeze-frame typically lasts around one second before the codec re-acquires the frame structure. It was observed that there were sporadic freeze-frames even when the codec was connected to a switch in the loop-back mode. This effect was attributed primarily to the small buffer size and the occasional off-sync condition.

The observed HDV results were similar to the ATM monitoring system results. When the weather in Hawaii was clear or had moderate cloud covers, the ACTS link generally ran error-free and the performance of the HDV was good. When it rained or when the cloud layer was thick in Honolulu, the ACTS link performance was poor and the HDV codec had a difficult time extracting frame synchronization information, resulting in many freeze-frames. Some of the freeze-frames could last several seconds as the ACTS link continued to be attenuated, particularly on the TAMC-to-JPL link.

9. FUTURE WORK

Transmission Control Protocol (TCP) level throughput performance was not measured. An SGI Challenge at SPHDC and a Sun Sparc-20 in Japan were very close to being fully prepared. The configuration would permit a TCP throughput test using the dual-satellite link.

Phase 2 of the experiment calls for the entire trans-Pacific link to operate at OC-3. This includes the upgrade of the Intelsat earth station at Kapolei and the use of the CRL earth station in Japan. The terrestrial ATM network bandwidth in Hawaii and Japan would need to be increased.

10. CONCLUSION

The Trans-Pacific High Definition Video Satellite Communications Experiment tested the ability of satellites to carry high definition video signals for post-production processing between Sony studios in Tokyo and Los Angeles and successfully established an end-to-end trans-Pacific broadband link. The relatively good results obtained encourage the construction of a global information infrastructure utilizing broadband satellite systems. Results of the experiment also suggest additional issues to be examined in enhancing various aspects of the information infrastructure, such as codec clock synchronization and link reliability enhancement. Some of these issues are planned to be investigated in the near future.

The combination of remote cinematography teams, real-time post-production equipment, and a satellite-based broadband network creates a virtual studio environment for the director. The remote teams, with portable HD monitors, can collaborate interactively with the director and post-production team over great distances. The director will have direct influence on live action photography and may receive repeated image generations from the remote teams with short turn-around time. The digital transmission system, utilizing the flexible communications links made possible by broadband satellites, brings distributed studio assets to cinematography teams at remote locations. In addition, remote HD monitors may be replaced by HD theaters which can receive direct broadcasts using the digital transmission system. The ability to make direct broadcasts increases the usefulness of the transmission system in applications such as tele-education and tele-medicine.

The success of this experiment demonstrates the feasibility of a global information infrastructure utilizing broadband satellites and is a result of seamless team work by an international group of participants. It marks an exciting beginning for the Trans-Pacific High Data Rate (HDR) Satellite Communications Experiments and is a significant achievement for the Global Interoperability for Broadband Networks (GIBN) project.

11. ACKNOWLEDGMENT

The research described in this publication is carried out jointly by the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration and the Communications Research Laboratory and Ministry of Posts and Telecommunications of Japan.

The authors appreciate the tremendous effort and support of all participants in this experiment: the ACTS Office and Control Room, BBN, Communications Research Laboratory of Japan, Comsat, George Washington University, GTE Hawaiian Tel, the State of Hawaii, Intelsat, JUSTSAP, Kokusai Denshin Denwa Company, Limited, Lockheed-Martin, Japanese Ministry of Posts and Telecommunications, Mitsubishi Electric Corp., NASA HQ/Code SM, GSFC, LeRC, Newbridge Networks Inc., Nippon Telephone and Telegraph, NREN, PacBell/CalREN, Pac Space, Sony Corp., SPHDC and TAMC. Without them, the experiment's successful outcome would not have been possible.